VTT Technical Research Centre of Finland

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Published in:
Journal of Cleaner Production

DOI:
10.1016/j.jclepro.2021.128113

Published: 15/09/2021

Document Version
Publisher's final version

Journal of Cleaner Production 315 (2021) 128113

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Toward a sustainable plastics value chain: Core conundrums and emerging solution mechanisms for a systemic transition

Jaakko Siltaloppi[a,*], Markus Jähi[b,c]

[a] Aalto University, School of Science, Department of Industrial Engineering and Management, P.O. Box 15500, FI-00076, Aalto, Finland
[b] VTT Technical Research Centre of Finland, Smart Industry and Energy Systems, P.O. Box 1300, FI-33101, Tampere, Finland
[c] Tampere University of Applied Sciences, School of Business, FI-33520, Tampere, Finland

ARTICLE INFO

Handling Editor: Dr. Govindan Kannan

Keywords:
Plastic
Sustainability
Sustainability-oriented innovation
Value chain
Qualitative research

ABSTRACT

In recent years, various environmental issues associated with plastics have become well documented, spurring a growing volume of research on the barriers, drivers, and solutions related to the development and commercialization of sustainable—bio-based, biodegradable and circular—plastics. However, a systemic perspective that addresses the complex interdependencies across the value chain has so far been missing from the analysis. Based on a qualitative study covering the entire plastics value chain in Finland and Northern Europe, this paper addresses the research gap with two main findings. First, the paper identifies three core conundrums that describe the complex and interrelated nature of technological, operational, economic, and societal factors, which are inhibiting the transition to sustainable plastics at three critical junctures of the value chain. Second, the findings describe four solution mechanisms, which suggest that the value chain actors need to shift (i) from the supply of bulk materials to material solutions; (ii) from firm-centric material development to cross-tier collaboration; (iii) from price competition to competition on sustainability benefits; and (iv) from isolated technologies to infrastructure development. These findings extend our understanding of the systemic challenges for the transition to a sustainable plastics economy and shed new light on the ways in which companies can address the challenges for a system-wide impact.

1. Introduction

Plastic is a versatile and cost-efficient material group with a large array of applications. Due to its strength, malleability, barrier properties, and cheap price, its use has grown steadily from 2 million tons in 1950 to approximately 380 million tons in 2015, and the growth is expected to continue (Geyer et al., 2017). In recent years, however, environmental issues with plastics have become well documented, including the growing greenhouse gas emissions of plastics production, and the leakage of plastic waste into the nature (e.g., Geyer et al., 2017; Jambeck et al., 2015; Worm et al., 2017; Zheng and Suh, 2019; see also EASAC, 2020). In response, national and international regulators, NGOs, and private companies are taking increasingly salient actions to address the identified issues (e.g., Dijkstra et al., 2020; Nielsen et al., 2020; see also Ellen McArthur Foundation, 2016).

In academia, the growing awareness of the environmental problems associated with plastics has created momentum for research exploring the obstacles of, and opportunities for, the transition to a sustainable plastics economy from technical, operational, economic, and regulatory perspectives (e.g., Confente et al., 2020; Leal Filho et al., 2021; Lettner et al., 2017). Notably, studies consider these questions from the perspective of different actors, including petrochemical companies (Iles and Martin, 2013; de Vargas Mores et al., 2018), plastic product manufacturers or converters (Paletta et al., 2019), consumer brand owners (Gong et al., 2020; Ma et al., 2020), retailers and consumers (Confente et al., 2020; Friedrich, 2020; Leal Filho et al., 2021), recycling operators (Huysveld et al., 2019; Pazienza and De Lucia, 2020), and policymakers (Nielsen et al., 2020; Leal Filho et al., 2019).

However, by focusing narrowly on one value chain tier or actor type, a more holistic perspective is largely missing in the literature on the

* Corresponding author.
E-mail addresses: jaakko.siltaloppi@aalto.fi (J. Siltaloppi), markus.jahi@tuni.fi (M. Jähi).

https://doi.org/10.1016/j.jclepro.2021.128113
Received 27 January 2021; Received in revised form 14 June 2021; Accepted 24 June 2021
Available online 25 June 2021

barriers, drivers, and potential solutions in transitioning to sustainable[1] plastics. In particular, the lack of a holistic perspective makes it difficult to understand and solve the problems of effective material circulation, which calls for simultaneous focus on technological, logistical, business, societal, and political processes across waste logistics, material processing, and product manufacturing (e.g., Kawashima et al., 2019; Nielsen et al., 2020; Simon, 2019). Similarly, transitioning to sustainable plastics in the manufacturing of plastic products, parts, and packaging is influenced by the complex interconnections between polymer producers, converters, brand owners or manufacturers, and recycling operators, as well as the influences of wider economic and societal changes (Paletta et al., 2019).

To this end, this paper extends the existing research on the transition to sustainable plastics by developing a holistic, systemic view of the entire plastics value chain from oil refinement to polymer production, conversion, retail, consumption, and recycling the material back into the value chain. Specifically, this paper has two objectives: first, to develop a systemic understanding of the barriers of the sustainable plastics transition, and second, to describe how organizations can address these barriers through new practices and solutions in innovation activities and business development. To meet these objectives, we conducted an exploratory qualitative study into the change barriers and emerging solution mechanisms across the plastics value chain in Finland and Northern Europe. By identifying three core conundrums that synthesize the development barriers for three critical junctures of the value chain, and describing four solution mechanisms with which organizations can address the conundrums, this paper extends our understanding of the systemic nature of the transition to a sustainable plastics economy.

The remainder of the paper is structured as follows. Section 2 provides an overview of recent literature on the barriers and drivers of the sustainable plastics transition, and develops a systemic perspective on the plastics value chain. Section 3, describes our research methodology. In Section 4, we present our empirical findings organized into two main parts, starting with the analysis of three core conundrums for the sustainable plastics transition, followed by the identification of four solution mechanisms to address these conundrums through means of sustainable business development. In Section 5, we conclude the paper by discussing our contributions to the literature and presenting avenues for future research.

2. Literature review

2.1. Barriers and drivers of the sustainable plastics transition

Recent research has begun to identify various factors that constrain, and enable, the transition to sustainable plastics in different parts of the plastics value chain, from polymer production to conversion, retail, and recycling (e.g., Iles and Martin, 2013; Gong et al., 2020; Paletta et al., 2019; Huysveld et al., 2019). In this section, we briefly summarize this literature by looking at the technological, operational, economic, and societal or regulatory barriers and drivers of transitioning to sustainable plastics.

First, the technological barriers mainly pertain to the novel or inferior material properties of both bio-based and recycled plastics (e.g., Dijkstra et al., 2020; Spierling et al., 2018; de Vargas Mores et al., 2018), which create new challenges for product designers and converters (Brockhaus et al., 2016; Paletta et al., 2019). Combined with their higher price in comparison to fossil-based plastics, new material properties limit the adoption of sustainable plastics in the market (Dijkstra et al., 2020; Lettner et al., 2017). The technological barriers also extend to the limitations of new technology, especially in plastics recycling, in which technological advancements are needed for sorting and processing plastics into high-quality raw material (Kawashima et al., 2019; Paletta et al., 2019), especially in chemical recycling (e.g., Larrain et al., 2020; Ragaert et al., 2017).

Operationally, studies identify the need for new types of supply chain relationships and material sourcing practices (Dijkstra et al., 2020). For example, new auditing practices are needed to create a supply chain for bio-based raw materials for polymer production (de Vargas Mores et al., 2018). Furthermore, limitations in the capacity of bio-based plastics production and plastics recycling constrain the wider applicability and rapid increase in the use of sustainable plastics (e.g., Gong et al., 2020). Resistance to the use of sustainable plastics also limits the increases in production, especially among converters (Paletta et al., 2019), and makes it difficult to change to the current supply chain management practices. The operational challenges extend to the brand owners and manufacturers, who lack competences in procurement and product design to enable the increasing use of bio-based and circular plastics (Brockhaus et al., 2016; Gong et al., 2020). As the collection, sorting, and processing of plastic waste remains inefficient and covers only small parts of the overall waste system (Paletta et al., 2019), the supply of circular plastics also remains limited and unfavorably priced for high-volume buyers (Dijkstra et al., 2020).

Economically, the higher cost of sustainable plastics makes them relatively unattractive to most industry players, especially when factoring in the additional obstacles of small production volumes and variable material quality (Paletta et al., 2019). For polymer producers, the superior feasibility of fossil raw materials is a significant hurdle (Iles and Martin, 2013). Converters, operating on small profit margins, are unable to carry the additional costs (Paletta et al., 2019), and even the large brand owners or retailers are willing to bear the extra cost only to a very limited extent (Friedrich, 2020; Gong et al., 2020), as these companies struggle with capitalizing on the benefits of bio-based and circular plastics (Dijkstra et al., 2020).

At the societal level, various regulatory and cultural barriers come into play. In terms of consumer demand, there is growing public awareness of the plastic waste problem and demand for more sustainable packaging alternatives (Leal Filho et al., 2021). However, the growing awareness is slow to translate into consumer behavior. Confente et al. (2020) suggested that consumers are willing to accept sustainable plastics if the value of the products and the environmental benefits are clear and there is a strong congruence with consumers' personal values. What makes things complicated is that there is a clear lack of measurement tools to demonstrate the benefits of sustainable plastics, and even basic definitions (e.g., "bioplastic") remain ambiguous (Gong et al., 2020). The quality of the product itself also remains a central factor in the purchasing decision and needs to be incorporated into the design of more ecological plastic products and packaging (Saari et al., 2018).

On the regulatory side, while new legislation is being introduced rapidly, especially in the EU, it remains underdeveloped in many ways. For example, waste legislation on the end-of-life of plastic is currently unspecified (Paletta et al., 2019), illegal waste exports continue from

[1] Plastics encompass a wide range of synthetic or semi-synthetic materials that are used for various consumer and industrial applications (Andrady and Neal, 2009). A distinction is often made between virgin, fossil-based plastics and so-called bioplastics. The latter comprises bio-based and biodegradable plastics: bio-based plastics refer to plastics produced out of bio-feedstocks, whereas biodegradable plastics refer to plastics that degrade in natural environments through biological processes. Moreover, "novel bioplastics" with a new chemical structure and material properties can be separated from bio-based plastics that imply a different origin but have the same chemical structure than the fossil-based, conventional plastics, such as polypropylene or polyethylene (e.g., Alaerts et al., 2018; Spierling et al., 2018). Finally, recycled or circular plastics are plastics processed either mechanically or chemically from plastic waste to create a useable raw material. By replacing the use of virgin plastics and avoiding the incineration of plastic waste, recycled plastics are also a more sustainable option (Huysveld et al., 2019). In the remainder of this paper, we use the label *sustainable plastics* to refer to bio-based, biodegradable, and recycled plastics. This category contrasts the linear plastics economy and the fossil-based virgin plastics.

Europe (Paletta et al., 2019), and the upcoming regulatory limitations to the use of plastics (e.g., the single-use plastics ban) are far from resolved (e.g., Ma et al., 2020). Furthermore, the current extended producer responsibility (EPR) systems in Europe are unharmonized and lack incentives for companies to push circular design across their products and packaging (Leal Filho et al., 2019). New problems also loom with growing recycling rates, as there are currently no tools to deal with waste segregation by waste generations (Dijkstra et al., 2020), nor strong alternatives to waste incineration in energy production (Paletta et al., 2019).

On the positive side, the literature also identifies clear drivers for the sustainable plastics transition. Above all, various technological and material advancements drive the sustainable plastics field forward (see, e.g., Kaur et al., 2018), and this is generally supported by environmental and social—as well as the long-term economic—considerations (e.g., Larrain et al., 2020; Lettner et al., 2017; Spierling et al., 2018). The developing regulation, in the EU and elsewhere, is speeding up the development of plastics recycling in particular (e.g., Dijkstra et al., 2020; Nielsen et al., 2020; see also, European Union's Plastics Strategy, 2018). Moreover, growing consumer awareness of the plastic waste problem, and sustainability at large, slowly but surely increases the market demand for sustainable plastics (Dijkstra et al., 2020; Gong et al., 2020). For example, recent findings located in Europe show that many consumers are aware of the problems associated with plastics and are willing to adopt sustainable options (Leal Filho et al., 2021).

2.2. Toward a systemic view of the plastics value chain

While the research discussed above offers valuable insights into the challenges and drivers of the sustainable plastics transition, the majority of this work tends to focus quite narrowly on the perspective of one value chain tier. While useful for understanding the specific contingencies of the different industrial sectors linked to the plastics value chain, this approach limits the consideration of how the barriers and drivers are interrelated across the value chain tiers in influencing the transition to sustainable plastics (e.g., Kawashima et al., 2019; Paletta et al., 2019). Furthermore, the narrow research focus can become limiting to the development of new practices for sustainability-oriented innovation. As the plastics value chain is fragmented into multiple tiers with distinct technological bases, business models, and market practices (Dijkstra et al., 2020; Lettner et al., 2017; Nielsen et al., 2020; Paletta et al., 2019), the absence of a systemic view can steer the innovation efforts to incremental, tier-specific improvements that are inadequate for driving up sustainability impact at a systemic level (e.g., Adams et al., 2016; Ritala et al., 2018). At worst, such innovation efforts can be detrimental for the wider systemic transition as they reinforce the current development trajectory (e.g., Johnson and Suskewicz, 2009; Korhonen and Seager, 2008; Markard et al., 2012) founded on a fossil-based, linear economy model.

The complex nature of sustainability challenges calls for systemic solutions that join value chain actors in new patterns of production, consumption, and economic exchange (Bidmon and Knab, 2018; Bolton and Hannon, 2016; Gallo et al., 2018; Rossignoli and Lionzo, 2018). This is particularly evident in the context of the circular economy, which requires collaborative innovation activities (e.g., Antikainen and Valkokari, 2016; Fehrer and Wieland, 2020) to leverage and align technological and operational developments with changes in business models, societal expectations, and regulations (Kawashima et al., 2019; Simon, 2019). Regulations and public incentives also play a role in forbidding unsustainable materials and supporting innovation activities in the direction of systemic sustainability and circularity (e.g., Cainelli et al., 2020; Edmondson et al., 2019; Friedrich, 2020; Stål and Corvellec, 2018). Notably, as policies can also inhibit system-level development toward sustainable practices through misaligned incentives—such as the EPR systems (Leal Filho et al., 2019)—accentuating the importance of close collaboration between private and public sectors in effecting systemic sustainability transition (Markard et al., 2012).

In Fig. 1, we outline a holistic and systemic perspective on the plastics value chain. In the figure, we bracket out three main tiers of the value chain based on the main material transformations performed in each tier: (i) raw material refinement (transformation of raw materials into polymers); (ii) manufacturing and distribution (transformation of polymers into plastic products, parts, or packaging distributed to consumers/users); and (iii) recycling (transformation of plastic waste into useable raw material through various collection, sorting, and processing stages). Based on this systemic view, our empirical study focuses on the challenges and emerging solutions associated with the transition to sustainable plastics. Using Fig. 1 as guidance, we trace the barriers of this transition by paying specific attention to how different factors (technological, operational, economic, and societal) interrelate in either inhibiting or driving the transition to sustainable plastics. Furthermore, we analyze emerging solutions that are tackling these barriers and identify solution mechanisms that address the systemic obstacles for change.

3. Research method

To understand the systemic barriers of, and emerging solutions to, the transition to sustainable plastics, we conducted an exploratory qualitative study of the plastics value chain based mainly in Finland (with four informants from other countries in Northern Europe). The qualitative research approach is suited for generating a generalizable understanding about a complex contextual phenomenon through an interpretive, inductive process (e.g., Denzin and Lincoln, 2005; Morgan and Smircich, 1980; Strauss and Corbin, 1998). In this paper, we adopted the qualitative approach to develop a detailed, contextual understanding of the barriers and solutions related to sustainable plastics with a focus on their interrelated, systemic nature.

We collected data through interviews and workshops (see Table 1). Compatible with the qualitative research approach, we approached the interviews and workshops from an interactionist perspective (Silverman, 1993). As opposed to taking the informant's statements as an objective fact, we conducted the interviews in an open-ended manner to gain insights into the ways in which our informants understood and experienced the complex arrays of challenges and had pursued new solutions related to sustainable plastics. This means that while we used a semi-structured interview guide to ensure that we covered the same topics in each interview, we allowed each interview to unfold following the informant's insights and reasoning (Fontana and Frey, 1994; Kvale, 1996). Their expert views and interpretations allowed us to gain rich insights into the systemic obstacles and solutions to the sustainable plastics transition.

We conducted 40 interviews, which were recorded and transcribed verbatim for analysis. We interviewed experts from private companies, public research organizations, industry associations, and national regulators, representing all tiers of the plastics value chain (see Appendix I for detailed information). We began the interviews by identifying key companies, industry associations, research institutes, and regulators in the plastics field in Finland and interviewed their representatives. These informants pointed us to other potentially interesting organizations and expert informants, which we subsequently contacted and interviewed. We continued this process until we reached theoretical saturation, that is, when the informants in each value chain tier were no longer introducing new insights into the research questions we posed (Guest, 2006).

We also organized three workshops to extend and validate the insights generated through the interviews. In the first workshop involving a multi-disciplinary group of researchers, a general understanding of the plastics value chain and its challenges was developed. The second workshop extended the identification of development barriers and drivers with a diverse practitioner group. The third workshop was used to validate and further extend our emerging observations on sustainable plastic solutions with a practitioner group. The first two workshops were

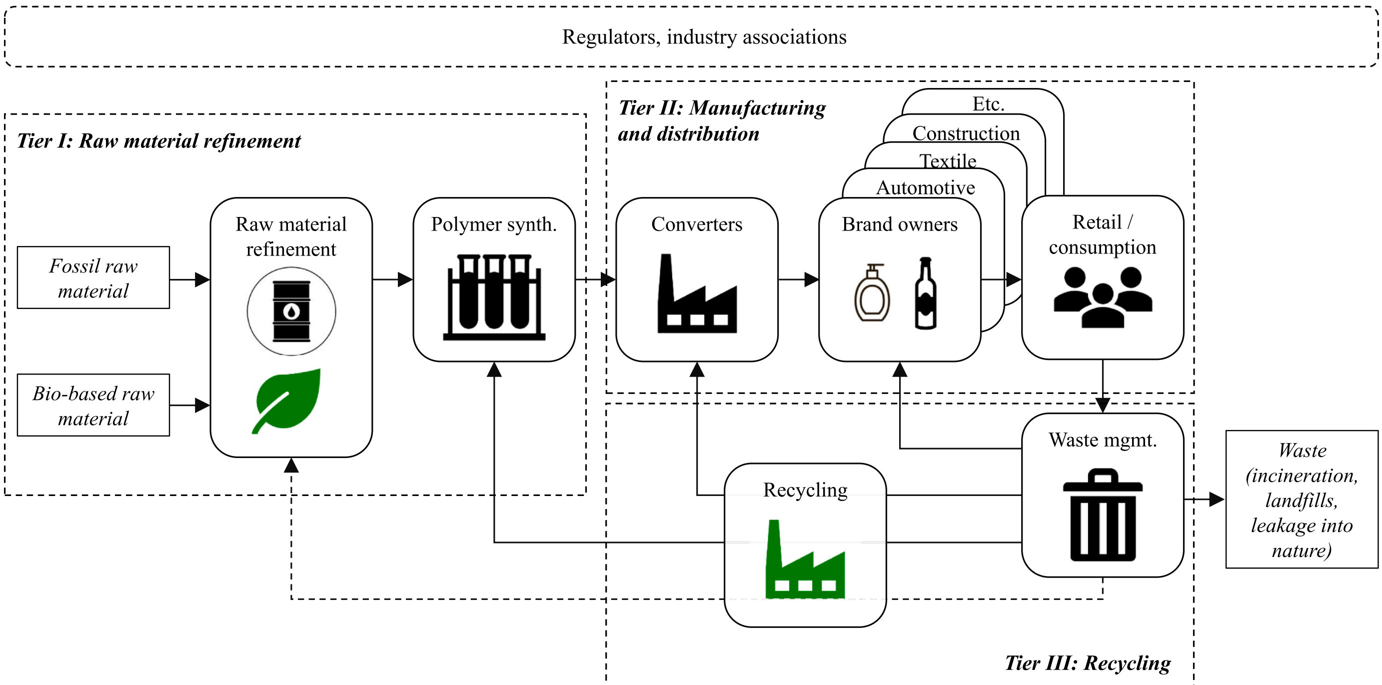

Fig. 1. The main tiers of the plastics value chain.

Table 1
Empirical data.

Type of data	Description	Use in data analysis
Interviews	*40 interviews (11/2019-08/2020).* Informants from all value chain tiers (see Fig. 1), including private, public, and non-profit organizations (see Appendix I). Total duration ca. 46 h.	• Identification of systemic drivers and barriers for the transition to sustainable plastics • Identification of emerging innovations and business solutions advocating sustainable plastics
Workshops	*WS1: Researcher workshop (09/2019)* Summarize and refine multi-disciplinary understanding of the sustainable plastics transition. 23 participants. *WS2: Industry experts (09/2019)* Identify the value chain challenges for sustainable plastics transition. 35 participants. *WS3: Industry experts and researchers (04/2020)* Validate emerging research observations and extend our understanding of solution scenarios. 47 participants.	• Extending our understanding of the barriers and drivers of sustainable plastics development • Validating our understanding of emerging sustainable plastic solutions and associated challenges and future business prospects

organized in person, and the findings were codified in the form of structured notes by the workshop hosts. The third workshop was organized virtually due to the outbreak of the global Covid-19 pandemic, and the input from the practitioners was collected for analysis with an online workshop tool.

We analyzed the data in an inductive manner (Strauss and Corbin, 1998) in two overlapping stages. In the first stage, we analyzed the interview data and observations of the first two workshops to develop a systematic understanding of the barriers to the sustainable plastics transition across the value chain. We began by reading through the empirical material and attaching descriptive codes to segments talking about specific obstacles or developmental avenues (i.e., open coding). Then, we combined similar codes into aggregate categories of transition barriers (axial coding), paying specific attention to each of the main value chain tiers. In this stage, we used visual and table formats to compare and group the change barriers (Miles and Huberman, 1994) and develop a deeper understanding of the interrelations among the identified barriers. As a result of this process, we were able to condense the initial list of identified change barriers into three core conundrums (presented in Table 2 below). Each conundrum captures a cluster of interrelated barriers pertaining to the sustainable plastics transition at one critical juncture of the value chain. In the spirit of the holistic and systemic view of analysis, the conundrums do not comprise isolated barriers or drivers but synthesize the ways in which technological, value chain related, economic, and institutional/regulatory elements intertwine. Section 4.1 presents the conundrums in detail.

In the second stage of data analysis, overlapping with the first one, we analyzed the empirical data for sustainable plastic solutions that our informants identified as promising or already used by organizations in the plastics value chain. After compiling a long list of solutions with short descriptions, ranging from new technologies to new materials and recycling concepts, we compared the solutions in light of the value chain conundrums identified in the previous step. Specifically, we sought to identify key elements underpinning the identified solutions in terms of how they addressed the systemic issues identified in the three conundrums. As a result of iteration between interview data and emerging findings, including particularly the practitioner observations from the third workshop, we condensed the empirical insights into four solution mechanisms. These mechanisms and the ways in which they tackle the conundrums are presented in detail in Section 4.2.

4. Findings

4.1. Conundrums of the sustainable plastics transition

Based on the empirical analysis of the barriers to the sustainable plastics transition, we identified three core conundrums that pertain to (i) the limited production of sustainable plastics relative to the production of virgin fossil-based plastics, (ii) the lack of uses and demand for sustainable plastics in industrial and consumer applications, and (iii)

Table 2
Barriers to sustainable plastics development around three core conundrums.

	Limited production of sustainable plastics	Lack of uses and demand for sustainable plastics	Missing economic logic for recycling development
Description	*Introducing sustainable plastics to a large-volume production system under conditions of limited raw material availability and uncertain demand.*	*Matching the technically limited and uncertain supply of sustainable plastics with uncertain and difficult-to-mobilize customer demand.*	*Creating momentum for the development and growth of the recycling infrastructure with costly processing and low value of circulate.*
Technological barriers	• Technology and production processes optimized for fossil feedstocks • Complexity of and limited capabilities in LCAs	• Inferior (or new) material properties of sustainable plastics • Manufacturing processes optimized for virgin, fossil-based materials	• Technology underdeveloped for sorting, mechanical processing and chemical recycling • Limited recyclability of certain waste streams (e.g., PVC, composites, multi-layer materials)
Operational/supply chain barriers	• Lack of actors and production capacity • Raw material scarcity/low availability • Mass production logic incompatible with small volumes • New demands for transparency	• Limited availability of sustainable plastics (especially high-quality circular plastics) • Limited demand/current applications • Fragmented supply chain inhibits collaborative development	• Dispersion of consumer plastic waste • Lack of recycling capacity and infrastructure • New plastics incompatible with current recycling schemes
Market barriers	• Low and uncertain market demand • Higher price of bio-based plastics • Competition with fossil • High investment cost in new production capacity	• Higher cost of bio-based plastics • Adaptation cost in the manufacturing processes • Sustainable packaging is not a strong driver of consumer purchase decisions	• Cost of processing and logistics exceed market value for most circular plastics • Limited demand for lower quality circular plastics
Societal barriers	• Limited regulative and societal pressure for fossil-free solutions • Ambiguity in certification and standardization • Environmental issues with increased use of bio-feedstocks	• Ambiguity or lack of regulation • Missing support for sustainable consumer choices (e.g., eco-labels)	• Uncertain global policies (e.g., import bans for plastic waste) • Lack of efficient supporting mechanism (e.g., taxation)

a missing economic logic for recycling development (see Table 2).

Each conundrum describes a cluster of interrelated the technological, operational, market, and institutional barriers (and enablers) identified in the empirical data as limiting the transition to sustainable plastics. By focusing on clusters of interrelated issues, the conundrums highlight the wicked nature of the transition barriers that intertwine to challenge organizations within each of the three main value chain tiers. More broadly, the conundrums also describe the systemic nature of the change barriers that interrelate across the value chain to call for systemic solutions. In the following sections, we discuss each conundrum in detail.

4.1.1. *Limited production of sustainable plastics*

In the raw material refinement tier, the core conundrum of the sustainable plastics transition pertains to the challenge of increasing the production of sustainable plastics relative to fossil plastics. As the feasibility of plastics production depends on massive production volumes, optimized currently for the use of fossil feedstocks, the technological, operational, market, and societal barriers coalesce to obstruct the scale-up of sustainable plastics. Our interview data reveal particularly how companies in this value chain tier struggle to find a sound business case for the mass-scale production of sustainable plastics due to limited raw material access and higher price, more complex supply chains, and uncertain customer demand.

Notably, our informants indicated that technology is not the primary limiter to scaling up sustainable plastics production. Rather, the conundrum lies in the lock-in with the current production model, which binds companies to existing installations, supply chains, and business models optimized for fossil raw materials. Breaking this lock-in requires significant investments in new refineries and petrochemical installations that utilize bio-based or chemically recycled feedstocks. As the price of bio-based or circular feedstocks is (almost always) higher than fossil feedstocks, only the most environmentally progressive customers are willing, at the moment, to pay the premium for a greener alternative. The fluctuating prices of crude oil further undermine the economic competitiveness of sustainable plastics.

The production of sustainable plastics also requires companies to develop new internal competences and external partnerships, which are difficult to establish and call for new relational practices. In the upstream, the procurement of bio-based or circular raw materials is drastically different from the global fossil market, as the number of suppliers and demands for transparency grow exponentially. In the downstream, new partnerships are needed with customers, as are improved methods for life cycle assessment (LCA) to trace and demonstrate the positive sustainability impact of the new plastics. Furthermore, raw material availability becomes a significant issue as operations are scaled up given the current limitations on how much plant-based raw material or bio-waste is available for plastics production, as illustrated in the following excerpt:

One deciding thing is raw material availability. To grow with renewables requires overcoming the challenge of extending and growing [the network] of raw material [supply]. (Interview 7, oil company).

To give an example of this conundrum, a company we interviewed had produced bio-based plastic with crackers optimized for fossil fuels in small batches for a few pioneering customers. The higher cost of the bio-feedstock was one notable obstacle. Furthermore, the batch production model caused additional challenges, first, in handling the bio-based batches separately from the fossil plastics, and second, in the need to adjust the cracker to using the bio-feedstock as opposed to fossil fuel for a short duration. While the focal customer in this case was willing to pay a higher price for the bio-based plastic, the example indicates that lowering the cost requires investment in continuous operation with bio-feedstocks in dedicated installations to drive down price and drive up production volume.

To further complicate the scale-up of the production of sustainable plastics, certain key questions remain open in the regulatory realm that further inhibit the scale-up of sustainable plastics production. One key issue mentioned was the lack of common standards and certification practices, which obfuscated the definition of "bioplastics" and the required bio-content. As the aforementioned example indicates, in batch production, it is easier for petrochemical companies to operate on a mass balancing model in which customers' purchase a certificate rather than plastic with measurable bio-content. Another set of issues pertains to regulations, which remain in their infancy with sustainable plastics. Although regulations such as the EU's Renewable Energy Directive (2009/28/EC) provide incentives for transitioning to renewable raw materials in plastics production, uncertainty persists in other areas—for example, in the regulatory treatment of the chemical recycling of plastic waste. This is captured in the following excerpt:

> I mean the main risk which I'm seeing is really […] with the changes in oil price is that we can [bring] this kind of renewable circular economy to a profitable level. […] Partly, at least, it will also depend on how the legislatures, the regulators will move forward on creating incentives to use renewable and circular solutions versus additional

> fossil based and linear economy approaches. (Interview 32, petrochemical company)

4.1.2. Lack of uses and demand for sustainable plastics

Shifting to the manufacturing and distribution tier of the value chain, a new set of barriers arises for increasing the use of sustainable plastics in various industrial and consumer products and packaging. Specifically, the main conundrum for the companies in this tier revolves around combining the limited, expensive, and technically constrained supply of sustainable plastics with their products in a financially feasible manner under the conditions of uncertain and difficult-to-mobilize customer demand. Our interviews showcase, in particular, how companies, despite an increasing supply of sustainable plastics and growing awareness of the plastic waste problem among consumers, struggled to mobilize this awareness into actual demand and willingness to pay for more sustainable product or packaging options. As one informant expressed,

> We know from consumer data and surveys that consumers expect more sustainable products and packaging, expect companies to make good choices, and we see that this has demand in the market. […] But I must say that the sales have not been overwhelming, and my guess is that while the consumers expect green products, recycled plastic, and recyclable packaging, it does not necessary translate into a purchase decision at the shelf. (Interview 37, brand owner)

To break down this conundrum further, one part of the problem originates in the novel and partly inferior technical properties of the sustainable plastics. While some polymers, such as bio-based polyolefins, are technically equal to their fossil-based counterparts, new polymers, such as polylactic acid (PLA), have altogether new material properties that are difficult to integrate into existing production processes and product designs, for example, due to increased process costs (e.g., van den Oever and Molenveld, 2017). With mechanically recycled plastics, their inferior technical properties and contamination risk constitute an additional limiter (Mehat and Kamaruddin, 2011), especially in demanding applications such as industrial components, medical applications, or food packaging.

Besides limiting the areas of application, each new material also increases the challenges in product design because the design must consider not only the use of new materials but also their impact on recyclability (Alaerts et al., 2018). Creating new product designs is challenging, as the necessary competences are divided between value chain actors accustomed to operating with standard designs and production practices. In this context, the new material properties give rise to particular challenges for the converters, as described in the following excerpt from a workshop:

> The converters have high barriers to changing the resins they use. [Converters are] often SME size companies, who are used to selected resins and suppliers. Changing raw material is costly and time consuming: How do we overcome this obstacle at the converting step in the [value] chain? (Comment, workshop 3).

Another central issue underpinning this conundrum is the limited material supply that partly relates to the issues of scaling up production discussed above. Coupled with their higher price, and with circular plastics of low and often varying quality, the limited material supply makes it difficult for brand owners or manufacturers to use sustainable plastics in high-volume applications, such as consumer packaging. On the flipside, for smaller manufacturers identified as forerunners with sustainable plastics, there seem to be more opportunities and supply from the smaller recyclers or material developers seeking applications for their material.

Pointing to the market and societal aspects, most of our informants recognized the positive impact of increasing consumer awareness and new regulation, especially in the EU, for the transition to sustainable plastics. That said, consumer brand owners, in particular, saw significant challenges in translating this growing awareness into actual purchase decisions, and hence monetize the use of sustainable plastics in their products or packaging even when technically viable (see also Confente et al., 2020). The evolving regulation was also a source of additional concern, at the time of the interviews, due to the ongoing debate around the limitations on, for example, single-use plastics. Many of our informants also mentioned the lack of regulation and standards as an issue, as it afforded opportunistic companies to exploit the green branding benefits with minimal use of sustainable plastics in their packaging. Relatedly, increased consumer awareness was also seen as necessary for creating demand for sustainable plastics.

4.1.3. Missing economic logic for recycling development

The risks associated with bio-feedstocks, such as erosion, deforestation, and competition with food production, were among the main reasons why the informants considered recycling as the more promising direction for increasing the sustainability of plastics production and consumption. However, in many parts of the world, the recycling infrastructure remains underdeveloped or non-existent, preventing the circulation of the material back into the value chain. Even in countries with advanced waste management, including Finland and large parts of Europe, the infrastructure for collecting, sorting, and processing plastic waste continues to require both technological development and investments in new capacity to achieve the ambitious recycling rate targets.

Our data highlight a number of interrelated issues that constitute the third conundrum inhibiting growth in plastics recycling. Specifically, the conundrum lies in the fact that while costly investments into collecting, sorting, and processing plastic waste are needed to return plastics into the value chain as high-quality recyclates, the low market value of plastic makes it difficult for private actors to invest in R&D and a new capacity without strong regulator involvement and enforcement. In other words, the question is how to drive up investments in recycling technology and services when the market price of most fractions does not cover even the operational costs, as highlighted in the following quote:

> What drives us is market demand for different waste streams, plus how effective it is for us to separate them. […] Currently, the price of plastic waste is negative. If I have mixed plastic waste, I have to pay to get rid of it. If this was otherwise, we could separate and process it. But currently it is unfeasible. (Interview 12, waste management company)

On the technical side of this conundrum, the barriers relate to the technologies for sorting and processing plastic waste. While pure, homogenous waste streams (e.g., industrial packaging waste and separately collected clear PET) can already be processed into high-quality recyclates that have a demand in the market, mixed consumer plastic waste remains much harder to sort and process with the current mechanical processing techniques into recyclates of adequately high quality. The reject percentage is also high. Many of the informants thus saw the chemical recycling of plastic—thus far in a developmental stage—as a necessary step to increase both the quality and quantity of plastic recycling.

On the market side of the conundrum, the negative value of plastic waste as input, and the low price of recyclates as output complicates the economic logic and makes the development of the plastics recycling infrastructure highly dependent on public regulation. The recycling operators must rely on gate fees to sustain feasible operation. However, gate fees make the value of plastic waste negative, meaning that the producers and/or collectors of plastic waste must pay not only for the logistics but also for the transaction at the gate. While regulatory schemes, such as the EPR system, can provide the needed push for recycling infrastructure development, they are not entirely predictable

Table 3
Four solution mechanisms.

Solution mechanism	Description	Conundrums addressed
1. From bulk materials to material solutions	New type of offering—Introduction of new sustainable plastics as easy-to-adopt solutions, based on • Applicability in current manufacturing processes • Consideration of sustainability and branding benefits	• C1: Limited production of sustainable plastics • C2: Lack of uses and demand for sustainable plastics
2. From firm-centric development to cross-tier collaboration	New actor roles—Adopting new roles to initiate collaboration across the value chain to develop and scale-up new material solutions through • Production coordination and support • Process and product design development	• C1: Limited production of sustainable plastics • C2: Lack of uses and demand for sustainable plastics
3. From price competition to competition on sustainability benefits	New market dynamic—Increase the use of sustainable plastics based on sustainability benefits, especially in the FMCG vertical characterized by • Competitive market dynamic and benchmarking • Ability to leverage sustainable product categories	• C2: Lack of uses and demand for sustainable plastics
4. From isolated technologies to infrastructure development	New assets—Systematic development of recycling infrastructure for plastics through multi-actor collaboration. Requires • Financial incentives for collecting and sorting plastic waste • Integration of chemical recycling effectively into the recycling value chain	• C1: Limited production of sustainable plastics • C3: Missing economic logic for plastics recycling

and can tilt the incentives in the wrong direction. For example, the current ERP systems incentivize the actors to establish collection schemes for plastic waste without having to consider circular designs or the use of circular raw materials in their products or packaging (e.g., Leal Filho et al., 2019). This array of challenges creates a curious situation in the plastics recycling market in Europe; there is, on the one hand, an oversupply of collected plastic waste due to EPR systems and bans on waste exports, yet, on the other hand, an undersupply of recyclates at desired quality levels due to an underdeveloped recycling system. Without an appropriate economic logic to incentivize the development of the recycling system across the entire value chain, supply and demand in the recycling tier appears to remain misaligned.

4.2. Toward solving the conundrums: advancing systemic transition in the plastics value chain

With the notion of the conundrum, we highlight how the identified obstacles to the transition to sustainable plastics are not merely isolated factors affecting the sustainable innovation and commercialization efforts of organizations in specific steps of the value chain. Instead, they cut across the technological, operational, market, and societal dimensions, and are deeply interrelated across the value chain tiers—as evident, for example, in the see-saw between questions of supply and demand (and relatedly, quality and cost). The fact that each value chain tier draws on distinct technologies, follows its own operational and business logic, and deals with unique innovation and market challenges adds to the challenge of developing sustainable plastic solutions that carry the potential for systemic change across the entire value chain.

By adopting a solution-focused stance toward the conundrums, our analysis identifies four different solution mechanisms that open avenues for a systemic transition in the plastics value chain. We summarize these in Table 3, and describe each in more detail in the sections below.

4.2.1. From bulk materials to material solutions

As the first solution mechanism, our data highlighted the importance of shifting from a narrow material-technological focus in material development to offer new, sustainable plastics as solutions for downstream customers. Referred to as "drop-in material solutions" by multiple informants, these material solutions support the adoption of sustainable plastics by improving the applicability of the new material in existing production processes, demonstrating the sustainability of the material to the customer, as well as potentially including other value-adding features such as product design support. For example, an oil company processing renewable raw materials can offer its renewable hydrocarbons for petrochemical companies as a drop-in feedstock that requires little if any adjustment to existing crackers. Similarly, the developers of new bio-based plastics or composites can benefit from developing their material to be compatible with existing injection molding or extrusion processes. Finally, recycling companies can add value to the recyclates by incorporating client-specific compounding. As expressed in the following excerpt, a "drop-in" solution can give a unique advantage in the market:

> This kind of concept does not exist elsewhere in the Nordics. It gives us a great opportunity as our customer can [focus on manufacturing], we can adjust the additives and compounds [...], tailor the product for our main customers. (Interview 15, recycling operator)

Besides material properties, the drop-in material solutions also include design or branding features that further justify the use of the new material for the client beyond the technical and economic questions. Material providers can, for example, demonstrate the sustainability of the material to their clients, who can further use the arguments in the marketing of their products to downstream customers. In one example from our data, the developer of a new biocomposite material also invested effort into material appearance and packaging design, creating a "turnkey" packaging solution for their clients seeking standout packaging for premium products. As summarized by their representative, the material solution in their case comprised three central elements:

> Our three main principles are sustainability, of course, but also the way it looks, the aesthetics. [...] And of course that the material works in the application we sell it to. (Interview 20, biomaterial developer)

As such, the drop-in material solutions address the first and second conundrums of the sustainable plastics transition in at least two ways. First, the drop-in material solutions support growth in the production and utilization of sustainable plastics by harnessing the existing production and manufacturing capacity for sustainable plastics. This is particularly important to converters operating with low margins and tight resources, as it enables them to apply new materials in an easy, low-cost manner. Second, the drop-in solutions can provide a way for material developers to avoid intense price competition against mainstream materials, allowing them to target more "premium" market segments in the early stages of scale-up when the price of the material remains higher. Besides easing the financial pressures associated with the scale-up of sustainable plastics production, the creative branding and marketing of the enhanced material solutions can also facilitate the appropriation of new uses for sustainable plastics in industrial and consumer applications.

4.2.2. From firm-centric development to cross-tier collaboration

Besides new material development, there is a growing impetus for cross-tier collaboration in the value chain to increase the adoption of sustainable plastics in various application areas. As implied in the discussion on the benefits of drop-in material solutions, the new sustainable plastics place more extensive demands on not only material development, but also the development of manufacturing techniques, product, or packaging designs, as well as branding and marketing. These demands call for the companies typically specialized in one of these areas to increase efforts in collaborative R&D and adopt new roles in the value chain to facilitate collaboration across value chain tiers.

Our findings draw specific attention to two critical roles that cross-tier collaboration plays in increasing the production and use of sustainable plastics. First, even when the material properties of sustainable plastics are not novel or inferior (e.g., with bio-based polyolefins), more intensive collaboration across the value chain tiers is important for coordinating production with intermediaries and customers. For example, with small production volumes, the batch production model requires the raw material supplier (e.g., an oil company), the plastic producer (e.g., a petrochemical company), and customer (e.g., a brand owner) to carefully arrange and coordinate the production and logistics of the material so that it can be produced and delivered promptly to match the established supply chains of the conventional materials.

Second, sustainable plastics with novel material properties increase the competence requirements necessary for developing materials for specific uses. Aligning material properties, production techniques, and product designs thus calls for close, iterative collaboration involving the material provider, converter, and client to optimize the use of the material for a specific use. New competences are particularly needed from the material developers to enable them to support the client in adopting the novel material in the product design. These new requirements are evident in the following quotation by a large plastics producer:

> We already have a few commercial applications, which we make together with our customers, or the converter and brand owner, [focused on] incorporating the recyclate or the bio-based material. […] To use the mechanically recycled material to replace virgin, we need more and more circularity-oriented designs for the packaging and there we are developing solutions to simplify multi-layer materials, to use materials that are compatible also when recycled. (Interview 29, petrochemical company)

With growing interest in more sustainable packaging materials and material circulation, large brand owners are also increasingly active in driving the development of sustainable plastics. One interviewed brand owner, in particular, had taken a vanguard role in its value chain to introduce circular plastics in the packaging of one of their product lines. Given the large volume of plastic needed, the brand owner bypassed the converter in purchasing the circular material to secure a large enough volume of supply. The brand owner also worked closely with the converter to adapt their process to the use of the circular material and, as evident in the following quotation, used the developed competences as the basis for subsequent projects involving the use of recycled plastics:

> We then sent our R&D teams, when it comes to packaging, to our supplier to help them with know-how in how to make bottles and then the processes for testing and innovating. […] We learned it [with the first partner] and now we can use it both in our own section and, I mean, we use multiple different bottle suppliers, so of course when we develop recycled plastic bottles, or our suppliers do, we can coach them with what we have learned on the way, obviously. (Interview 25, brand owner)

Thus, our findings highlight that besides the importance of material innovations, the developers of new materials or products need to provide new forms of support for their value chain partners in adjusting, adapting, and making the optimal use of sustainable plastics. To realize the new forms of support, new value chain roles become increasingly important for pioneering companies to facilitate collaborative development and the scale-up of production (addressing conundrum 1). Furthermore, cross-tier collaboration seems essential for creating new, technically viable applications to drive the demand for sustainable plastics (addressing conundrum 2).

4.2.3. From price competition to competition on sustainability benefits

Underpinning the growing importance of multi-tier collaboration is the fragmented plastics value chain that has been largely based on arm's length relationships. Besides complicating collaborative development, price-focused competition has made it difficult for companies across the value chain to incorporate sustainability benefits in their predominantly economic calculations on competitiveness and profits. At the same time, the growing consumer awareness about the environmental issues associated with plastics is not translating into purchasing decisions, with research suggesting that only a small group of "green consumers" make their purchasing decisions based on environmental criteria (see also Confente et al., 2020; Ottman, 2011).

However, with growing consumer expectations toward sustainable products on the one hand, and the threat of growing regulations and sanctions associated with the plastic waste problem on the other, our interviews indicate that brand owners are beginning to make salient commitments to sustainable plastics, especially in the FMCG vertical. We identify two factors, in particular, that translate sustainability benefits into competitive factors. First, the distinct competitive dynamic characterized by high visibility and constant benchmarking of innovative solutions means that sustainability features allow brand owners to stand out from the competition in the consumers' eyes by selecting sustainable packaging options. For the largest brand owners in particular, being a forerunner with such sustainable solutions is important for building a favorable brand image, as explained by one informant:

> I think if you are as big as [our company], you don't have choice. […] If you are big you need to be responsible, you are kind of more accountable for your actions than any other. (Interview 22, brand owner)

Second, the wide range of brands and product categories for FMCG brand owners allows them to adopt sustainable plastics incrementally, one product or brand at a time. This means that depending on the quality, availability, and price of sustainable plastics, as well as the ability of the converters to process them, large brand owners are able to gradually scale up the use of sustainable plastics while closely monitoring consumer feedback and market developments. However, as recent research suggests, the sustainable product or packaging options introduced cannot fail to satisfy the basic needs of the consumers related to the products themselves (Saari et al., 2018). This means that brand owners need to focus concurrently on the "functional" and sustainability benefits of their products to increase the consumption of more sustainable products and packaging materials.

Although incremental in nature, this brand owner-driven transition can have a significant impact on addressing the lack of uses and demand for sustainable plastics (conundrum 2) due to the massive consumption of plastics in FMCG packaging. The fiercely competitive market dynamic means that innovations in this area are likely to quickly diffuse as a result of benchmarking between brand owners, as well as growing competences among value chain actors to procure, design, and process sustainable materials developed through new forms of collaboration, as discussed above. Furthermore, our data indicate that brand owners and retailers play an important role in influencing consumer attitudes and purchase decisions toward more sustainable alternatives. While this change may be slow and shaped by various cultural forces (e.g., Ottman, 2011), the options afforded by brand owners and retailers play a role in the long-term transition, as suggested in the following excerpt:

> Organic is a good example. It started small, but now the prices of organic products are very close to regular ones, and more and more people buy them. […] As a retailer, we can indirectly steer the

> consumers to use the responsible products. Seasonal produce is a good example; we have been able to increase their sales through campaigns and pricing of course. [...] That leads to growing demand which diversifies the product repertoire as well. But it's slow, there is no magic button. (Interview 39, retail cooperative)

4.2.4. *From isolated technologies to infrastructure development*

A significant restraint to the increasing production and use of sustainable plastics is the limited availability of circular and bio-based plastics. Without a significant increase in raw material availability, the innovative material solutions, successful collaborations, and salient brand benefits will not translate into a large-scale transition to sustainable plastics. Against this backdrop, the findings of our interviews accentuate the need for a shift from isolated, firm-specific technology development to systematic infrastructure development in plastics recycling to scale up the volume of plastic that circulates back into the value chain as raw material.

Two interrelated elements stand out in our data as critical components for advancing infrastructure development. First, the collection and sorting of plastic waste is an enormous global challenge and requires new models that incentivize this for both consumers and waste management companies. In our study context, Finland, municipalities and the EPR organizations play a central role in the development of plastics recycling. However, other avenues exist for the development of enhanced recycling. The interviews raised several examples of FMCG brand owners, as well as oil and petrochemical companies, that are driving the development of plastics recycling through partnerships with waste management companies. The incentive is there: The oil and petrochemical companies strive to access renewable (and potentially cheaper) raw material streams for their operation to align their business with the long-term sustainable development goals, while the FMCG brand owners are pressed to address the plastic waste problem on their part while also needing circular raw materials in growing quantities to meet the (slowly) changing consumer preferences at the shelf. As described by an informant whose company is developing a private, market-based model for collecting plastic waste,

> [T]hese major brands like Nestlé and Unilever and so on are going out and saying that by 2025 we're going to have 100% recyclable material and so on. But the thing is that it doesn't matter if something is 100% recyclable, if it's not collected. [...] The big brand [owners] that we're in contact with want to produce more and more of their packaging with recycled material, but there's not enough recycled material. So they see, by connecting to our system, that okay, if we can actually make sure that more is recycled, then they can actually start having a factory where they can use recycled material instead of virgin. (Interview 34, recycling start-up)

Besides advances in collection and sorting to increase the amount of plastic recycled, the second key element frequently mentioned by our informants for creating an efficient and effective recycling infrastructure was chemical recycling. While largely under development at the moment, this umbrella of technologies (e.g., depolymerization, gasification, and pyrolysis) is seen as the basis for a leap in recyclate quality as it breaks the polymers down into monomers or hydrocarbons that can be produced into virgin-quality plastics. Assuming that these intermediary products are, or can easily be made, compatible with current petrochemical processes, chemical recycling can increase the production of sustainable plastics limited by the availability of sustainable biofeedstocks (addressing conundrum 1). Chemical recycling can also increase the market value of plastic waste and improve the economic equation for plastics recycling (addressing conundrum 3). For example, it can allow recyclers to tap new raw material streams in existing landfills.

However, to function properly, chemical recycling calls for the development of the entire recycling infrastructure. Besides effective collection, more advanced sorting of plastic waste streams is crucial for directing the waste material streams to make optimal use of different processing technologies at the systemic level. Overall improvements in plastic recycling also call for redesign and capacity building in handling the growing flows of plastic waste, including logistics for waste streams that are largely overlooked today:

> It also requires a change in thinking. Today, we consider only consumer packaging [as recyclable plastic waste]. We forget that half of all plastic [used] comprises car bumpers, dashboards, and sewage pipes. These continue to be incinerated. Nobody thinks about these or includes them in the calculations. (Interview 8, consultancy company).

This development, as discussed above, depends on the collaborative efforts of multiple actors, including brand owners, waste management and recycling operators, technology developers, and oil and petrochemical companies. Systemic change is called for not only in the collection of heterogeneous plastic waste streams, but also in the utilization of circular plastics in the value chain.

5. Discussion and conclusion

5.1. *Implications for research*

Recent research has begun to explore the barriers and drivers of sustainable—that is, bio-based, biodegradable, and circular—plastics from technological, operational, regulatory, and economic standpoints. However, a more holistic, systemic perspective has been largely missing in the literature, as the studies have focused primarily on factors specific to one value chain tier or type of application at a time (e.g., Gong et al., 2020; Confente et al., 2020; Iles and Martin, 2013; Nielsen et al., 2020; Paletta et al., 2019). To develop a systemic understanding of the factors contributing to the transition to sustainable plastics, we conducted an exploratory qualitative study to investigate the systemic barriers and potential solutions related to this transition. First, our findings identify three core conundrums, which highlight the complex and interrelated nature of the technological, operational, economic, and societal barriers within and across the value chain tiers. Second, we pinpoint four solution mechanisms that are central to the innovation and business development activities of organizations and show the potential for facilitating systemic change toward a sustainable material economy in the plastics value chain.

The findings make three main contributions to the literature on the transition to sustainable plastics. First, this paper outlines a holistic and systemic view for the research on sustainable plastics transition. While the systemic perspective is increasingly recognized as being central to understanding and creating impact with sustainability-oriented innovations and business models (e.g., Adams et al., 2016; Bidmon and Knab, 2018; Fehrer and Wieland, 2020; Rossignoli & Lionzo, 2018; Schaltegger et al., 2016), this paper draws on the systemic perspective to conceptualize and investigate the challenges of, and potential solutions for, the sustainable plastics transition. By extending the systemic perspective to the plastics value chain, this paper responds to recent calls for fuller, systemic approaches to understand and solve the environmental, social, and economic challenges pertaining to the production and consumption of plastics (e.g., Kawashima et al., 2019; Nielsen et al., 2020; Paletta et al., 2019; Simon, 2019).

Second, the analysis and synthesis of the change barriers into three core conundrums empirically enriches and complements our understanding of the challenges of the sustainable plastics transition. Whereas recent work has mapped the change barriers focusing on one value chain tier at a time (e.g., Friedrich, 2020; Gong et al., 2020; Huysveld et al., 2019; Iles and Martin, 2013; Paletta et al., 2019), this paper holistically analyzes how the technological, operational, economic, and societal factors intertwine within and across value chain tiers in the process of developing and commercializing sustainable plastic solutions. As such, the identified conundrums—related to the scale-up of sustainable plastics production, use, and recycling—highlight the complex and unique environments in which organizations operate vis-à-vis sustainable plastics in the material production, product manufacturing, and recycling tiers. Furthermore, the conundrums direct future research attention to the difficulties that arise at the nexus of the value chain tiers when actors co-operate using different technologies, partnerships, and business models while dealing with evolving societal pressures and regulatory constraints.

Third, this paper contributes to the literature by identifying and elaborating four solution mechanisms that allow organizations to address the conundrums through means related to business development. The solution mechanisms propose a shift (i) from the supply of bulk materials to material solutions; (ii) from firm-centric material development to cross-tier collaboration; (iii) from price competition to competition on sustainability benefits; and (iv) from isolated technologies to infrastructure development. These findings extend, in particular, the business-focused research emerging around sustainable plastics (e.g., Dijkstra et al., 2020; Iles and Martin, 2013) by refining current understanding of the ways in which private companies and other organizations can speed up the development and scale-up of the adoption of sustainable plastics. While the identified solution mechanisms are likely only a partial answer to the core conundrums, they describe concrete, novel ways in which companies can leverage the positive change drivers to tackle the central barriers to the wider transition in the value chain. Moreover, the conceptualization of the solution mechanisms, based around changes to the offerings, actor roles, competitive dynamics, and infrastructure, echo the importance of changes to all parts of (sustainable) business models (e.g., Boons & Lüdecke-Freund, 2013). As such, our findings create grounds for a more in-depth analysis of the role of business model innovations for systemic transitions in the plastics context (e.g., Bidmon and Knab, 2018; Bolton and Hannon, 2016), as well as more generally on the transition mechanisms across the plastics value chain. For example, drawing on the growing literature on sustainability transitions (e.g., Markard et al., 2012), future work is needed to extend our understanding of how these four, and other, solution mechanisms contribute to a system-wide transition in the plastics context.

5.2. Managerial and policy implications

The findings of this study also have implications for managing the transition to sustainable plastics in companies as well as in the regulatory sphere. In broad terms, the findings provide practitioners with a fuller understanding of the systemic barriers and possible solutions to the sustainable plastics transition. For managers in private companies, the findings call for particular attention to change in the business models and collaborative innovation and business development activities to create more sustainable—and feasible—models across the plastics value chain. For example, our findings spur companies to expand their value chain roles to support collaborative innovation across the value chain.

For regulators, the findings of this paper further highlight the complex landscape for policymaking in the plastics context. While the overall targets for regulatory actions seem fairly clear (i.e., reduction in plastic waste and overall greenhouse gas emissions), the findings of this study indicate that the impact of new regulations on technological, operational, and business development across the entire value chain is far from clear-cut. We are particularly eager to caution policymakers against regulatory actions that lead companies to adopt practices that optimize actions in one value chain tier without considering the (potentially) detrimental implications of those actions at systemic level. For example, the evolution of the EPR schemes might benefit from broadening the view on producer responsibilities and their impact on the recycling system more broadly.

5.3. Limitations and future research

Our findings come with certain limitations. Methodologically, the qualitative research approach is suited for exploring and creating new conceptual insights into complex phenomena such as the "socio-techno-economical" transition to sustainable plastics (Denzin and Lincoln, 2005). However, the approach does not permit statistical generalizations about the phenomenon in question. Thus, future research is needed to further investigate the relative importance of the various change barriers for different actors and the complex ways in which the identified change barriers limit the transition process in different scenarios.

Relatedly, our broad focus on the entire plastics value chain means that we have traded off specificity and detail for a holistic analysis. This is a justified choice, as it allowed us to reframe and extend the already voluminous literature on the transition barriers and drivers. However, additional research is needed to further investigate—both qualitatively and quantitatively—the solution mechanisms in the context of specific industry and company cases to provide a more detailed understanding of how companies can embark on and speed up the sustainable plastics transition. For example, future research could explore the exact ways in which oil and petrochemical companies can develop new materials as solutions and leverage multi-tier collaboration in commercializing and scaling up these solutions (e.g., Iles and Martin, 2013) or how companies weave together collaborative R&D, brand benefits, and infrastructure development for effective circular models (e.g., Beulque and Aggeri, 2016).

Our data were collected primarily in Finland, which positions our findings in the context of Northern Europe and the EU. In this context, policy and regulation are the major driving forces for bio-based, biodegradable, and circular plastics. In Northern Europe, the recycling infrastructure is also relatively advanced and based on the central contributions of municipal waste operators and EPR organizations. Importantly, consumer awareness of sustainable alternatives to fossil-based plastics is also growing in this part of the world (Leal Filho et al., 2021). Globally, this is a very distinct setting for investigating the barriers and development avenues for sustainable plastics and plastics recycling in particular. While we have attempted to be mindful of the contextual bias vis-à-vis the reality of plastics production, recycling, and the underlying causes of the plastic waste problem globally, our findings nevertheless relate primarily to the challenges and further improvements within an already advanced context. Future research is therefore needed to investigate and further extend our insights to contexts in which the infrastructure for the separate collection and processing of plastic waste is missing, or in which regulatory challenges result in the uncontrolled dumping of plastic waste into nature.

Finally, we see fruitful avenues for future research by connecting the research on the plastics industry and the sustainable plastics transition more firmly with the growing literature on sustainable innovation, business models, and the management of organizational transitions toward sustainability (e.g., Adams et al., 2016; Boons and Lüdeke-Freund, 2013; Loorbach et al., 2009). Two research avenues stand out to us as particularly promising. The first relates to developing a more detailed analysis of sustainable innovation and business model development (see also Dijkstra et al., 2020), specifically with a focus on cross-tier collaboration, which appears increasingly important for creating and scaling up sustainable plastic solutions. Such an analysis can enrich previous research that has focused predominantly on incremental firm-centric innovations. The second future research direction relates to investigating the underlying "root causes" of the conundrums inside organizations and the organizational-level transition processes. For example, management's knowledge about sustainable options and systemic challenges might be the underlying issue that prevents sustainable innovation and collaboration across value chain tiers (e.g., Quist and Tukker, 2013), as might be their risk aversiveness and cognitive focus on the business case (e.g., Hahn et al., 2014). Furthermore, because the integration of sustainability and business is laden with tension, the transition to sustainable solutions makes strategic and innovation management much more difficult (Hengst et al., 2020; Siltaloppi et al., 2020). Hence, future research is encouraged to examine these and other organizational-level factors in more detail.

CRediT authorship contribution statement

Jaakko Siltaloppi: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Markus Jähi:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research received funding from the Academy of Finland, Strategic Research Council.

APPENDIX I. INTERVIEWS

Interview	Company/Industry	Informant(s)	Date	Duration (min)
1	Forestry company	Development manager	11.11.2019	83
2	Chemical company	R&D manager	12.11.2019	104
3	Chemical industry association	Senior expert	14.11.2019	107
4	Product prototyping	Founder, CEO	18.11.2019	78
5	Plastics industry association	Expert	19.11.2019	91
6	National research institution	Expert	19.11.2019	45
7	Oil company	Project manager, R&D	20.11.2019	90
8	Consultant company	Senior consultant	22.11.2019	67
9	3D printing technology company	Founder, CEO	25.11.2019	77
10	Medical instrument company	Senior scientist	26.11.2019	89
11	3D printing technology company	Founder, CEO	27.11.2019	55
12	Waste management company	Director, recycling operations	5.12.2019	50
13	Municipal waste management company	Manager, business development	11.12.2019	71
14	Non-profit plastics recycling company	CEO	11.12.2019	84
15	Waste processing/recycling company	Project manager, R&D	13.11.2019	91
16	Ministry of environment	Expert, circulation and waste	29.1.2020	61
17	National environment institute	Expert, end-of-waste	4.2.2020	58
18	Plastics wholeseller	Development manager	10.2.2020	77
19	Non-profit R&D organization	CEO	12.2.2020	87
20	Biomaterial developer	Manager, sustainability	13.2.2020	76
21	Plastics product manufacturer	Director, sales and marketing	17.2.2020	64
22	Brand owner	Manager, PR and communications	18.2.2020	87
23	Plastic product manufacturer	CEO	3.3.2020	69
24	Plastic product manufacturer	Director, plastics production	9.3.2020	91
25	Brand owner	Director, marketing	9.3.2020	52
26	Building product manufacturer	CEO	26.3.2020	60
27	Oil company	a. Manager, R&D program b. Product manager	31.3.2020	86
28	Forestry company	R&D manager Research advisor Project manager	6.4.2020	83
29	Petrochemical company	Manager, R&D Expert, R&D	7.4.2020	49
30	Patent authority	Manager, customer relations Expert, chemical industry	8.4.2020	42
31	Oil company	Product manager	23.4.2020	46
32	Petrochemical company	Director of innovation	30.4.2020	51
33	Beverage packaging recycler	CEO Manager, stakeholder relations	4.6.2020	58
34	Recycling start-up	Founder, CEO	17.6.2020	45
35	Recycling start-up	Founder, CEO	18.6.2020	57
36	Plastics industry association	CEO	25.6.2020	71
37	Brand owner	Junior brand manager	29.6.2020	60
38	Food product manufacturer	Deputy managing director	1.7.2020	47
39	Retail cooperative	Manager, CSR	5.8.2020	55
40	Brand owner	Director, R&D and CSR	13.8.2020	51
	TOTAL			**46h 5min**

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